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Evidence for strong shear velocity reductions and velocity gradients in the lower mantle beneath Africa

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Abstract. We present data which indicate that the broad, low shear velocity anomaly beneath southern Africa is stronger and more extensive than previously thought. Recordings of earthquakes in the southwestern Atlantic Ocean at an array of broadband seismic stations in eastern Africa show anomalously large propagation time delays of the shear phases S, ScS, and SKS which vary rapidly with epicentral distance. By forward modeling, we estimate that the low velocity anomaly extends from the core–mantle boundary about 1500 km up into the mantle and that the average shear velocity within this structure is 3% lower than in standard models such as PREM. Strong velocity contrasts exist at its margins (2% over about 300 km). These seismic characteristic are consistent with recent numerical simulations of lower mantle mega–plume formation.

1. Introduction

Global seismic models of shear velocity variation suggest the presence of an extensive low shear velocity structure in the lower mantle beneath Africa (Figure 1). This seismic structure is the most anomalous large–scale structure in Earth's lower mantle and is likely the signature of a hot upwelling that may be the cause of the high long–wavelength geoid over Africa [*Hager et al.*, 1985] and the elevation of the southern African continent and sea floor of surrounding oceans [*Nyblade and Robinson*, 1994].

The seismic models of Figure 1 also have fundamental differences. While sg94 contains low shear velocity structure in this region primarily in the lowermost 200 km of the mantle with maximum shear velocity reductions of 5% in some locations, models s16u6l8, s12wm13, and s16b30 have smoother and lower–amplitude velocity variations in the lowermost mantle and low seismic velocity structures extend from the core–mantle boundary (CMB) several hundred kilometers into the mantle. Given these model differences, even the large scale structure of the African lower mantle anomaly is uncertain and thus the geodynamic modeling and interpretation of this mantle region is compromised.

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2. New Constraints on the African Lower Mantle Anomaly

We analyse data from selected stations of the Global Seismic Network and stations from a one–year deployment that operated in Tanzania [*Nyblade et al.*, 1996]. These stations form a dense linear array in eastern Africa with an aperture of about 30°. Earthquakes in the Drake Passage, Sandwich Islands, and Hindu Kush are at similar azimuth from these stations and at distances suitable for studying S, ScS, and SKS phases.

Large (> 12 s) travel time delays with respect to the Preliminary Reference Earth Model (PREM) [*Dziewonski and Anderson*, 1981] of S (T_S), ScS (T_{ScS}), and SKS (T_{SKS}) (Figure 2) imply that these seismic phases propagated through extremely low shear velocity structure, while the opposite trends of T_{SKS} and T_S reflect the profound influence of strong seismic velocity gradients in the deep mantle.

2.1. Magnitude of the velocity reduction

Differential travel times between ScS and S (denoted as T_{ScS-S}) and between S and SKS (T_{S-SKS}) are ideal for the study of the lower mantle because they are only weakly affected by upper mantle heterogeneity and errors in earthquake location. We obtain T_{ScS-S} data from recordings of events in the Sandwich Islands and Hindu Kush regions, and T_{S-SKS} data from recordings of an earthquake in the Drake Passage. The differential travel times are measured by waveform cross–correlation with an uncertainty of about 1–2 s and compared against model predictions, computed by 2–D ray tracing, in Figure 3.

We use a deliberately simple model of shear velocity variation appropriate for the cross-section A–A′. This schematic model is based primarily on model s12wm13 and contains a single low–velocity structure with uniform shear velocity reduction. Guided by the ray geometry, we systematically modify the shape and average shear velocity reduction of this structure in a forward trial–and–error procedure to improve the match to

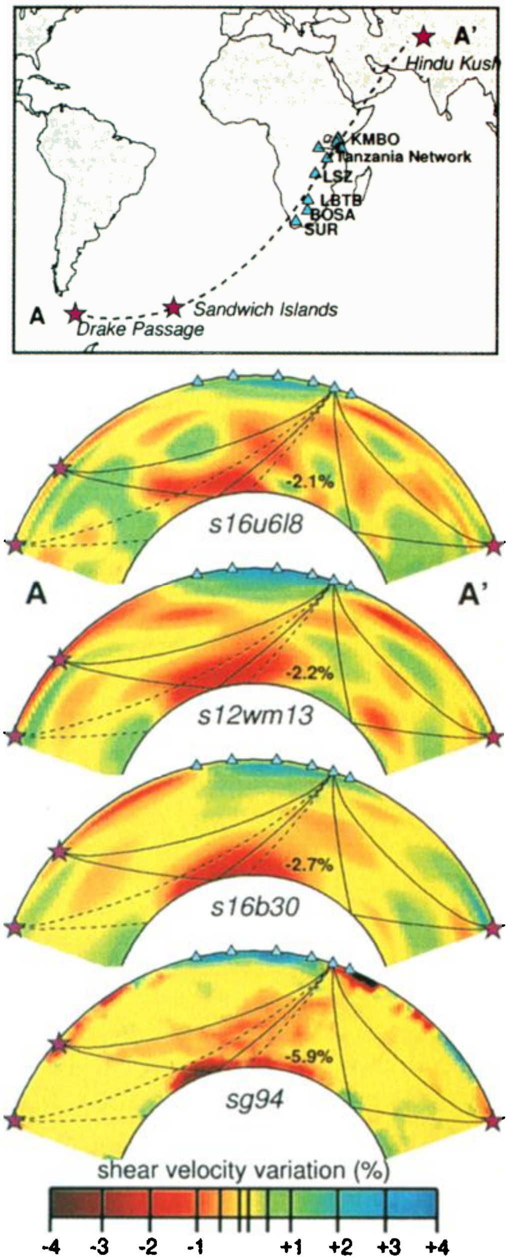

Figure 1. (top) Map indicating the location of seismic stations (triangles) and earthquakes (stars) used in this study. The dashed line indicates great circle arc A–A′. (bottom) Mantle cross-sections along A–A′ through models s16u6l8 [*Liu and Dziewonski*, 1997], s12wm13 [*Su et al.*, 1994], s16b30 [*Masters et al.*, 1996], and sg94 [*Grand*, 1994]. The solid lines superposed on the cross sections represent S and ScS ray paths from events in the Sandwich Islands and Hindu Kush regions to station MBWE in the center of the Tanzania Network. Dashed lines represent S and SKS path from an event in the Drake Passage to this station.

T_{ScS-S} and T_{S-SKS}. The average shear velocity reduction and the spatial extent of the low velocity structure can be robustly estimated, although the precise shape and internal velocity fluctuations remain largely unconstrained by our limited data set.

The derived model M2 provides an improved match to the magnitude and slope of the differential travel time data compared to the models from Figure 1 by introducing a stronger shear velocity reduction (~3% from PREM) and a larger extent of the African lower mantle anomaly (~1500 km above the CMB) into the mantle. Model M2 explains the T_{ScS-S} data for the Sandwich Islands events which systematically increase from 2 s at 45° to 12 s at 65° as ScS propagates along a progressively longer path through the southwestern margin of the low–velocity region. The decrease of T_{ScS-S} from 12 s to 8 s begins at 66° when S grazes the top of the low–velocity structure and T_S increases with increasing distance faster than T_{ScS}. T_{S-SKS} anomalies for

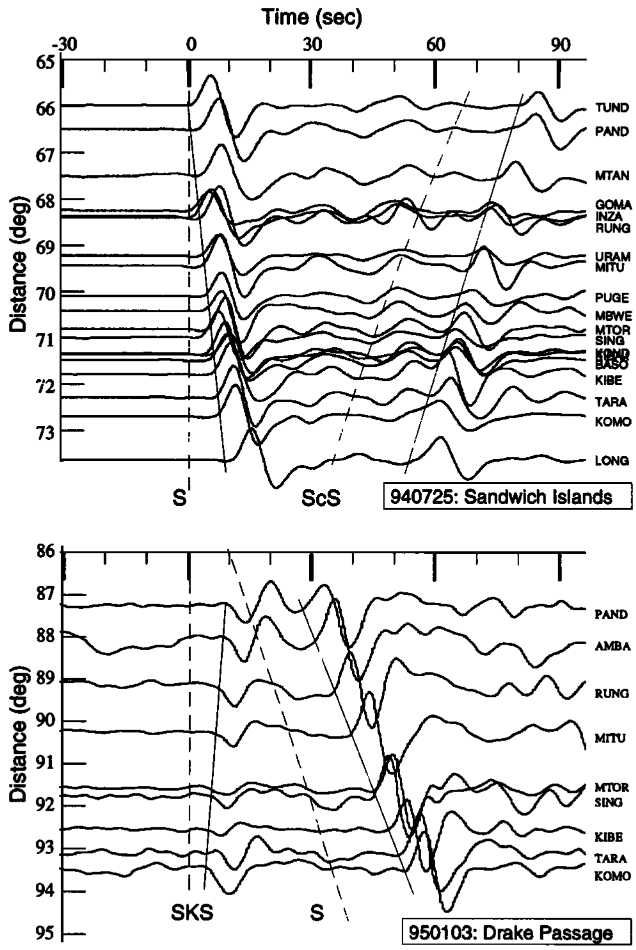

Figure 2. Tanzania Network recordings of (top) event July 25, 1994 in the Sandwich Islands and (bottom) event January 3, 1995 in the Drake Passage regions. The recordings are offset vertically by epicentral distance and associated station names are given to the right. The transverse component recordings of event 940725 are aligned on the predicted S arrival time for the PREM model. The radial component recordings of event 950103 are aligned on the predicted SKS arrival time. The slanted dashed lines indicate the arrival times predicted by PREM for ScS S, and SKS. Solid lines accentuate the general trends of the arrival times of these phases.

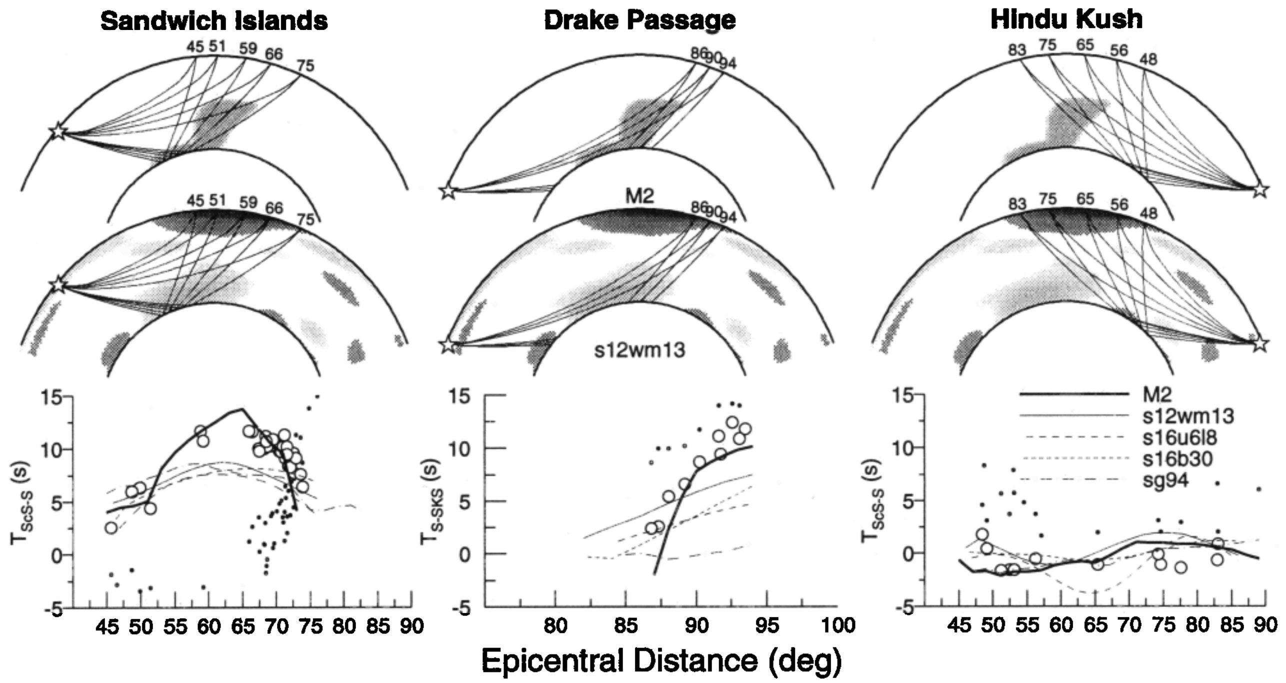

Figure 3. Comparison of models s12wm13 and M2 in the vertical cross section A–A′. Superposed are ray paths of *ScS* and *S* (for events in the Sandwich Islands and Hindu Kush) and ray paths of *S* and *SKS* (for the Drake Passage event). The stars indicate the event locations. Epicentral distances of the rays are plotted along the top. The measurements of T_{ScS-S} and T_{S-SKS} (open circles) and and model predictions are shown below the cross sections. T_S measurements are shown by solid small circles.

the 950103 Drake Passage event monotonously increase from 2 s to 12 s over the 86°–94° interval as the path length of *S* through the low velocity anomaly increases and the path length of *SKS* through the northeastern flank of anomaly decreases. T_{ScS-S} anomalies for Hindu Kush earthquakes beneath Pakistan do not show the large travel time delays as seen from the southwest. *S* and *ScS* propagate with similar path length through the northeastern top of the upwelling to stations in southern Africa at distances larger than 75°. Although corresponding T_S and values are generally less than 5 s, these positive values are clearly in contrast to the negative T_S values observed for events in the Sandwich Islands at the same stations.

2.2. Shear velocity gradients

Strong shear velocity gradients at the margins of the low shear velocity anomaly are included in M2 to explain the strong and reverse trends of T_S (Sandwich Islands) and T_{SKS} (Drake Passage) seen in the recordings of Figure 2. These trends persist after correction for travel times delays (up to 8 s) caused by seismic heterogeneity in the upper mantle beneath the Tanzania Craton and East African Rift [*Ritsema et al.*, 1998].

The mild increase of T_S for event 940725 in the Sandwich Islands region is well explained by s12wm13 for distances less than 71° (Figure 4). However, T_S at station LONG (73.6°) and station KMBO (74.1°) are, respectively, 3 s and 5 s larger than at station KOMO (72.6°) and implies that the velocity gradient near the turning point of *S* is much stronger than contained in s12wm13. The strong increase of T_S, associated with the decrease of T_{ScS-S}, can be reproduced if a shear velocity drop of about 2% across the uppermost region (~300 km) of the low velocity anomaly sampled by *S* is incorporated.

The decrease by 6 s of T_{SKS} for event 950103 in the Drake Passage from station TUND (87°) to station KOMO (93°) provides even more compelling evidence for the presence of a strong shear velocity transition at the margin of the low velocity anomaly, since this trend is opposite to the trend expected for upper mantle heterogeneity beneath the stations. A shear velocity change of about 2% over a lateral distance of 300 km (approximately the ray separation in the lower mantle of *SKS* waves traveling to 87° and 93°) along the 1500 km high northeastern flank of the low–velocity anomaly of M2 can explain the observed T_{SKS} variation. An even stronger shear velocity gradient is necessary if the change of T_{SKS} is accumulated over a shorter distance.

3. Discussion and Conclusions

This study presents new seismic data that indicates that the low seismic shear velocity structure beneath Africa is stronger (3% lower than PREM) and more extensive (from the CMB to 1500 km up into the mantle) than presented in previous models. Furthermore, strong travel time variation of relatively short epicentral distance range suggest strong shear velocity gradients (~2%/300 km) at some of the boundaries of this structure.

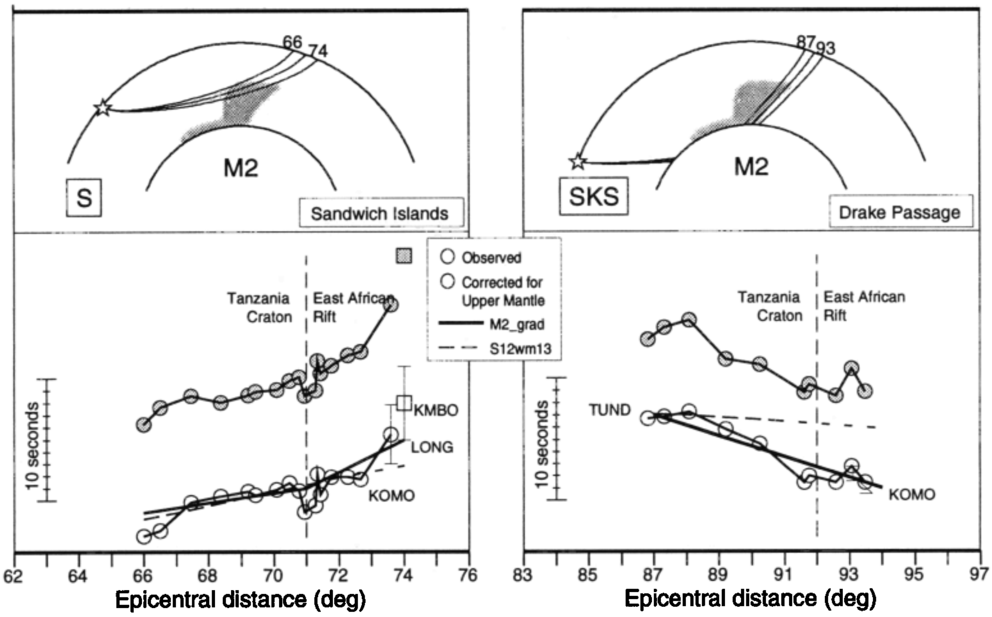

Figure 4. Comparison between the observed (circles) epicentral distance variation of T_S for event 940725 in the Sandwich Islands (left) and T_{SKS} for event 950103 in the Drake Passage (right) with predictions for models s12wm13 (dashed line) and M2 (solid line). The grey circles are the uncorrected delay times, while open circles represent delay times after corrections for upper mantle heterogeneity have been applied. *S* and *SKS* ray paths superposed on model M2 are shown above the data to illustrate the sampling regions of *S* and *SKS* at the margins of the low velocity anomaly where sharp shear velocity gradients are resolved.

Recently, numerical simulations have shown the possibility of 'mega-plume' (~1000 km radius) formation in a compressible mantle with strong temperature– and depth–dependence of viscosity and other thermodynamic parameters [e.g. *Zhang and Yuen*, 1997; *Thompson and Tackley*, 1998]. In these models, small-scale instabilities merge into a large plume attached to the CMB by a broad conduit that rises quickly and flushes the entire hot boundary layer above the CMB into the upper mantle. The strength, extent and the sharp boundaries we resolve for the African low velocity structure are the expected seismic characteristics of such a mega–plume.

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